## BELLCOMM, INC.
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SUBJECT: Thermal Considerations of the Perpendicular-to-Orbit-Plane and Gravity-Gradient Orientations for the AAP 1-2 Orbital Workshop Case 620

DATE: June 5, 1968

FROM: J. E. Waldo

## ABSTRACT

A review of the Orbital Workshop and Mission AAP 1-2 from a thermal viewpoint indicates there are few significant differences between the POP and GG attitude orientations. Those thermal considerations that are significant favor POP. Penetration and bulkhead leaks are lower in POP, and temperatures at these points are less likely to cause condensation or exceed astronaut touch limits. The temperatures in the POP cold case are the same as or higher than in the GG cold case. Cold-case requirements for electrical heating occur during the period of high available power in POP and low available power in GG; and the POP coldest case is less likely to occur - two times a year for POP and 16 times a year for GG. No significant differences are found in the means for thermal control, probable accuracy of thermal predictions, requirements for testing, or effectiveness of testing.

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## MEMORANDUM FOR FILE

## INTRODUCTION

The AAP 1-2 baseline attitude orientation was changed from Gravity-Gradient*(GG) to Perpendicular-to-Orbit-Plane (POP) in October 1967. Both orientations have advantages that are being reviewed. The purpose of this memorandum is to identify the thermal considerations that are different for POP and GG and to assess, if possible, their significance. In several cases, this is done using data insufficient for a definite judgment.

This memorandum considers the thermal environment and its extremes during a 28-day, 230 NM, 28 1/2° mission. Orbital Workshop (OWS) thermal control is currently semi-passive; that is, the only active components are cabin and duct fans, heaters, and associated control components. The OWS, equipment, crew, and experiments are assumed to be the same for POP and GG. The primary sources of OWS thermal data are studies by MSFC and the McDonnell Astronautics Company (MCASTRO).

Thermal considerations of attitude orientation appear in the mission environment, which determines orbital incident heating loads and in the OWS internal loads and temperatures. Additional possible considerations are the different means for the thermal control for POP and GG, the effects of having the AAP 1-2 orientation similar to the storage phase or AAP 3-4 orientations, and possible differences in the thermal analyses and tests.

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\* The use of the term gravity-gradient to describe a vehicle orientation is inaccurate. It confuses torque with attitude. Since it is widely used within the Program, GG will be used herein to refer to the local vertical orientation of the axis of minimum moment of inertia in accord with current usage.

The attitude conditions assumed in this study for POP, GG, the storage phase, and AAP 3-4 are:

During AAP 1-2, the OWS is oriented POP with the plane of the solar array perpendicular to the ecliptic plane and solar fixed; or the OWS is oriented GG with the solar panels articulated to an optimum angle for a given orbit and with a continuous OWS roll rate equal to the orbital rate.

During the storage phase, the OWS is oriented in a GG attitude with the plane of the solar array perpendicular to the OWS symmetry (X) axis.

During AAP 3-4, the OWS and solar panels are solar oriented with the OWS symmetry axis parallel to the ecliptic plane and the plane of the solar array perpendicular to the ecliptic plane.

Recent studies indicate additional active thermal control would improve OWS thermal and humidity conditions. This memorandum does not consider these proposed changes or the details of the current OWS status, except where a significant difference might be expected between the POP and GG orientations.*

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*    The following documents are suggested for detailed information concerning thermal control in the OWS:  OWS ECS Δ PDR Data Package, MSFC R-PV&E, December 2, 1967; Orbital Cluster Trade-off Study, MCASTRO, November 17, 1967; and Minutes of the AAP ECS/Thermal Subpanel Meetings 1 through 7.

CONSIDERATIONS

## Mission Altitude and Duration

Variations from the 230 NM altitude would change the solar and earth incident loads. Lower altitudes increase earth-reflected solar and earth-emitted IR radiation loads and reduce the duration of exposure to solar loads.

Changes from the 28-day mission duration would change the range of environmental conditions for a given mission but would not change the worst-case conditions affecting OWS design. The range of conditions is discussed in the section Influence of Angle β.

The thermal effects for the POP and GG attitudes of small variations in mission altitude and duration are not expected to be significantly different.

## Values of S, $E_A$, $E_{IR}$, $\alpha$, and $\varepsilon$

A range of values for environmental and surface coating characteristics is applied to establish worst-case conditions for analysis. For example, lowest values of the solar constant, earth albedo, and earth-emitted IR are used with unfavorable, degraded values of surface absorptivity and emissivity (and minimum internally generated heat) to determine the worst cold case. The effects of variations of these parameter extremes are not expected to be significantly different for the two orientations.

## OWS Equipment, Crew, and Experiments

Temperature limits and thermal loads imposed by the equipment, crew, and experiments are not expected to be different for the two orientations.

## Active ECS for Cooling and Humidity Control

Recent studies for the baseline POP orientation indicate additional active thermal control and changes in the OWS external coatings and duct arrangements would improve thermal and humidity conditions. No reported data indicate that present OWS problems could be dealt with better if the orientation were GG.

## Penetration and Bulkhead Heat Leaks

Heat leaks are of interest for net heat balance; for condensation points, which will be discussed later; and because of astronaut touch limits of 55°F to 105°F. Current data show the touch limits are exceeded at several points in the OWS. Heat leak effects on the net heat balance can be large and can vary significantly, depending on the attitude orientation. MSFC has reported that POP penetration heat leaks are approximately in balance, i.e., net zero, but that there would be a net heat loss in the comparable GG case.* Bulkhead losses can be significant and are greater in GG than in POP. Current studies are attempting to establish practical insulation schemes for minimizing the bulkhead losses. Figures 1 and 2, from the OWS ECS ∆PDR Data Package, show aft-end heat losses for the GG, POP, and solar orientations with an internal radiation heat shield and for the uninsulated case. Data for forward-end and total end heat losses are similar and indicate greater losses for GG than for POP.

## Crew Comfort Criteria

There is no reason to expect that crew comfort criteria would be different for POP and GG. However, these criteria establish significant temperature limits within the OWS and should be described.

The crew comfort envelope prepared by MSFC is based on MSC/MRO data and MSFC analyses of a thermal model of a man. The significant parameters are metabolic rates (500 to 1500 Btu/hr), clothing resistance (CLO values .025 to 1.0), atmosphere velocity (15 to 100 ft/min), atmosphere temperature, and mean radiant temperature (thermal curtain temperature). These comfort data were based on a specific humidity value of 0.018 lb $H_2O$/lb atmosphere, which is the low design limit. The crew comfort envelope is used to illustrate the capability of the OWS system to maintain a comfortable environment. OWS curtain and gas temperatures are plotted with respect to this envelope in Figure 3. The broken lines at 45° gas and curtain temperatures indicate the dewpoint for a specific humidity of 0.018. This is the temperature at which fog or surface condensation would occur.

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\* Private communication, W. O. Randolph, MSFC, April 26, 1968.

## Humidity

Humidity levels specified for crew comfort limit the allowable atmosphere and wall temperatures. Fogging and uncontrolled condensation are avoided if these temperatures are kept above the dewpoint - ideally, the dewpoint corresponding to the maximum specified humidity. In the actual case, dewpoints and temperatures are lower, and some surfaces are cold enough to cause condensation. In the extreme, condensation on surfaces below 45°F (broken line, Figure 3) dehumidifies the atmosphere to levels that are unacceptable for crew comfort.

This establishes low temperature limits for thermal curtains, interior walls, and penetration heat leaks; which is a reason why cold-side temperatures for the POP and GG orientations are important.

## OWS Thermal Analyses

This section discusses the relative thermal characteristics of POP and GG in terms of OWS interior temperatures, and identifies possible reasons for conflicting analytical results in the GG cold case.*

Detailed thermal analyses of the OWS have been reported only by MSFC (supported by Martin-Denver) and MCASTRO. Figure 3 shows reported temperatures of the OWS atmosphere, thermal curtains, and interior wall surfaces. Three cases analyzed by MSFC and MCASTRO are shown: POP cold, GG cold, and POP hot. The GG hot case has not been reported by either source. The single points by MSFC represent minimum curtain and average atmosphere temperatures using average external orbital heating. The envelopes by MCASTRO represent the range of atmosphere, curtain, and wall temperatures encountered in orbit, considering the transient effect of external orbital heating.

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\*     Incident thermal flux for the several different cases discussed in this section is approximated for an eight-sided cylinder in Appendix A. This material is from a memorandum in preparation by J. W. Powers, "Spacecraft Shadowing and Thermal Flux Programs."

Cold- and hot-case temperatures are outside the desired limits of the crew comfort envelope. All atmosphere temperatures for the cold cases are below the 45°F dewpoint, indicating fogging; and part of all thermal curtain and wall temperature ranges fall below the dewpoint, indicating surface condensation. Therefore, both MSFC and MCASTRO data show that the OWS cannot meet the coldest case with passive thermal control in either POP or GG; and active thermal control is required for the hot case.

An accurate comparison of the relative POP and GG thermal characteristics is not possible from the data in Figure 3 because MSFC and MCASTRO used different temperature representations (coldest vs. range), different solar array angles (fixed vs. variable), different roll profiles (fixed vs. continuous roll), and different analyses (steady state vs. transient). The differences in the MSFC and MCASTRO analyses of the GG cold case are listed in Table A. In spite of these differences, the data in Figure 3 are of interest, particularly for the cold cases. The cold cases are for the worst β angles and 1,000 Btu internal heat generation, that is, the passive case without thermal control heaters.

The MSFC cold cases for POP and GG differ; the GG atmosphere temperature is about 18°F colder than POP, and GG curtain temperature is about 20°F colder than POP.

The MCASTRO cold cases for POP and GG are approximately the same; the range of atmosphere temperatures, curtain temperatures, and wall temperatures differ by a few degrees.

The MCASTRO cold cases are closer to the MSFC POP cold case than the GG cold case, but cannot be said to be in agreement with the MSFC POP cold case.

MSFC found that the total incident flux to the sidewalls was about the same for POP and GG, but that the GG sidewalls had a cold side location on which the average incident flux was about half that for a similar cold side location for POP. This resulted in lower internal wall and thermal curtain temperatures at that location. The MSFC analysis assumed fixed solar arrays parallel to the OWS symmetry axis.*

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\*      Following this, variable solar array angle was proposed and adopted at the Baseline Review of October 12-13, 1967. MSFC has not thoroughly re-analyzed the GG cold case; but, on the basis of some brief analyses, feels the GG cold case would still be colder than the POP cold case. Private Communication, W. O. Randolph, April 26, 1968.

Differences in the GG Cold Case Analyses
by MSFC and MCASTRO

| | MSFC | MCASTRO |
|---|---|---|
| Roll profile | Low β, Constant roll angle, roll 180° during 30° subsolar sector.<br><br>High β, Optimum roll | Continuous roll |
| Loads and Losses<br><br>Sidewall<br>Bulkhead<br>Penetration | Analyzed separately<br><br>Orbit average<br>Orbit average<br>Orbit average | Combined in one thermal model<br>Transient<br>Transient<br>Transient |
| Internal Heat Generation | 1,000 Btu | 1,000 Btu |
| Solar Array<br><br>Angle<br>Shadowing<br>Blocking<br>Exchange | <br><br>$0°$<br>Included<br>Included<br>Included | <br><br>$41°$<br>Not included<br>Included<br>Included |
| Temperatures<br><br>Atmosphere | <br><br>25°F, total atmosphere average temperature, average over orbit. | <br><br>34.5 to 42.4°F, variation over orbit and location in OWS. |
| Thermal curtain | 13°F, coldest node for orbit (worst case). | 23.8 to 51.7°F, variation over orbit and circumference. |
| Wall | Not reported. | 10.8 to 66.1°F, variation over orbit and circumference. |

MCASTRO used a solar array angle of $41^{\circ}$, which pivoted the arrays to the cold side of the OWS. The MCASTRO analysis shows that the presence of the arrays increases the net incident load to the GG cold side location by blocking the view to deep space and increased reflection and IR exchange from the arrays. MCASTRO reports that this effect and the difference in roll profiles explain the difference in the GG cold cases.

Considering the above data and the accuracy expected in thermal analysis, it appears to be fair to say that the GG coldest case is as cold as, or colder than, the POP coldest case. And, therefore, the GG heater requirements will be as large as, or larger than, the POP heater requirements during the coldest case.

Influence of Angle $\beta$

Angle $\beta$ is the minimum angle between the earth-sun line and the orbital plane. $\beta$ histories for 230 NM orbits of a $28.5^{\circ}$ inclination are shown in Figure 4.* OWS attitudes with respect to the sun for POP and GG at the extreme $\beta$ angles of $0^{\circ}$ and $53^{\circ}$ are shown in Figure 5. The worst cases, hot and cold, occur at the extremes of $\beta$. At $\beta = 0^{\circ}$, POP is hottest and GG is coldest; at $\beta = 53^{\circ}$, POP is coldest and GG is hottest. The frequency of these worst-case conditions and the probability of their occurrence are of interest because of the influence on thermal design, particularly in the degree of active thermal control. For the hot cases, active control requires removing heat through the Airlock ECS; and for the cold cases, active control requires adding heat to the OWS through electrical heaters, which involves the electrical power and $\beta$ angle relationship to be discussed later.

Referring to Figure 4, the period of the $\beta$ envelope variation is one year. For a particular launch time, the peak-to-peak period is 45.4 days and the number of crossings at $\beta = 0^{\circ}$ is 16 times a year. Therefore, the extreme conditions for POP and GG occur as follows:

$\beta = 0^{\circ}$, POP-hot, GG-cold, 16 times per year, and

$\beta = 53^{\circ}$, POP-cold, GG-hot, 2 times per year.

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\* Figure 4 and its text and Figure 6 are from a paper by W. W. Hough and B. D. Elrod, Solar Array Performance as a Function of Orbital Parameters and Spacecraft Attitude, to be presented at the ASME Aviation and Space Conference, June 16-19, 1968.

These are the extreme β conditions that, in general, indicate the regions and frequency of hot and cold β for POP and GG.

Under random launch conditions, a 28-day active mission can span several combinations of thermal conditions that may be favorable or unfavorable. One cycle in β variation from peak-to-peak is about 57° with a period for the full cycle of 45.4 days. A 28-day mission is slightly greater than one-half this cycle. Referring to Figure 4 again, several examples of extreme hot and cold conditions can be seen for both POP and GG. At the center of the figure the one-half cycle can start near either 0° or -53° and end near -53° or 0°; or the one-half cycle can be biased around 0° or -53°.* To the left in Figure 4 (at about '90'), the one-half cycle can span peak-to-peak +33° to -33°, approximately; or the one-half cycle can begin near 0°, peak at 30°, and end near 0° again.

These examples show that at least one, and possibly both, of the worst-case conditions will exist for both POP and GG in a 28-day mission. It appears, therefore, that for random launch conditions both the hottest and coldest worst cases should be considered and designed for.


Cold-Case Heater Requirements

It is of interest to consider the minimum difference in available power, and the difference in coldest-case available power for POP and GG.

Average continuous power available at load as a function of β is shown in Figure 6. "Sun-oriented array" is representative of POP, and "continuous roll rate" is representative of GG. Optimum array angle is used in both cases. Points A indicate the minimum

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* Positive and negative β have the same effect.

difference of about 6%.  If the ordinate 100% value is assumed
for convenience to indicate 10 KW, then this 6% difference is
equivalent to about 600 w.*  This indicates the available power
from POP is at least 600 w greater than for GG.  The point has
been made in the past that POP has a 300 w penalty for attitude
control heating not required in a GG cold gas system.  The above
600 w difference indicates the ACS heater penalty is not significant.

          The coldest case for POP is when $\beta = 53°$, indicated on
Figure 6 by point B.  The coldest case for GG is when $\beta = 0°$,
indicated by point C.  It is during these periods that the highest
heater electrical loads would be expected; and it is at these
conditions that available power is maximum for POP, about 5.2 KW,
and minimum for GG, about 3.4 KW.  This indicates the available
power during the coldest case is about 1.8 KW greater for POP,
or about 50% more than GG.

          In general, the region of high $\beta$ angles is the coldest
for POP and is also the region of highest available electrical
power.  The region of low $\beta$ angles is the coldest for GG, but is
the region of lowest available electrical power.  These conditions
favor POP, where there is a good match between the occurrence of
required and available electrical power.  A second point favoring
POP is that the coldest condition occurs two times a year for POP,
but 16 times a year for GG.

Storage Phase and AAP 3-4

          Ideally, a thermal control design can be optimized for
a single, unchanging situation either by using a fixed orientation
toward all thermal sources or by spinning to smooth out variations.
Neither approach applies in AAP 1-2; but POP provides a closer
match to the AAP 3-4 orientation and its incident loads; and GG
provides a closer match to the GG storage orientation.  The GG
storage mode is inactive, and passive methods will be important.
However, because of wide temperature limits and lack of roll
control, it appears to make little difference in the storage phase
whether the OWS is GG or POP in AAP 1-2.

          Similarity with AAP 3-4 and reduced importance of
similarity in the storage phase favor, slightly, the POP orien-
tation for AAP 1-2.  This difference is not significant.

Means for Thermal Control

          POP and GG attitude orientations might be expected to
offer different means for thermal control because of mission-related
options and flexibility, and allowable or required differences

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          *If the actual value of $P_{SA}$ = 10,650 watts is used, then the
6% indicates 639 w.

in spacecraft design and operation. These means could be passive or active. A few examples have been noted in other sections.

For example, avoiding unfavorable β angles will reduce electrical power requirements for cold-case heating. POP can avoid the coldest conditions more easily than GG simply because β = 53° occurs only two times per year and β = 0° occurs 16 times per year. However, as concluded before, designs should be for the worst case. Avoiding unfavorable β angles may help the mission but should not affect the design.

Thermal coating schemes based on solar orientations appear to be more applicable to POP; and, because of POP and AAP 3-4 similarity, a coating approach favorable to both orientations appears more likely.

POP is favored slightly by mission options and similarity with AAP 3-4; but it appears that POP and GG have no differences that allow or require significantly different means in thermal control.

## Thermal Analysis and Testing

It was of interest to determine if there are differences in the POP and GG attitude orientations that would significantly affect the relative accuracy of thermal predictions, the requirements for thermal testing, or the effectiveness of thermal testing.

The results of thermal analyses depend on the accuracy of the analytical model to represent the spacecraft and its environment, including incident and internal loads, exchange between modules, and an accurate thermal model of the spacecraft components. For the OWS, this becomes incredibly complex. For example, shadowing, blocking, reflections, and view factors affecting the incident loads and radiant exchange between cluster modules in the presence of articulated solar arrays are being determined experimentally and analytically. In general, thermal analysts seem pessimistic and prefer to have thermal tests to verify and improve the thermal models.*

Thermal analyses are useful in indicating trends and differences; however, the combined errors and extreme complexity overshadow any differences in the POP and GG attitude orientations that would affect the relative accuracy of thermal predictions.

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\*      Error estimates vary from $\pm10°F$ to $\pm20°F$ and greater. Some recent data indicate about 85% of the measured temperatures in Apollo/Saturn flights are within $\pm20°F$ of the predicted values.

For the same reasons, primarily complexity, there appear to be no significant differences that would affect the requirements for testing or the effectiveness of thermal tests used to verify and improve thermal models or to qualify the thermal design.

ASSESSMENT

Few thermal considerations are both significant and also significantly different for the POP and GG attitude orientations. The thermal considerations identified during this study favor POP.

Thermal Considerations Favoring POP:

- Cold-case temperatures are less sensitive to solar array angles and are not a function of variable roll profiles.

- Penetration and bulkhead heat leaks are lower, and temperatures at these points are less likely to cause condensation and exceed astronaut touch limits.

- Temperatures in the cold case are the same as or higher than in the GG cold case. Cold-case requirements for electrical heating occur during the period of high available power in POP and low available power in GG.

- The coldest case is less likely to occur - two times a year for POP and 16 times a year for GG.

Thermal Considerations Favoring GG:

- Heating requirements for the attitude control system are less. This difference in total electrical requirements is not significant.

Thermal Considerations Essentially the Same for POP and GG:

- Mission duration.

- Equipment, crew, and equipment temperature limits.

- Active ECS requirements for thermal and humidity control.

- Crew comfort criteria.

- Means for thermal control.

- Probable accuracy of analytical predictions.

- Requirements for testing.

- Effectiveness of testing.

- Orbit altitude.

- Variations in solar constant, earth albedo, and earth IR.

- Thermal coating degradation.

- Thermal coating schemes.

- Similarity to storage and AAP 3-4 orientations.

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Attachments
    Figures 1-6
    Appendix A

Note: Dashed line indicates maximum POP Mode orientation heat loss for J-2 engine facing ecliptic plane.
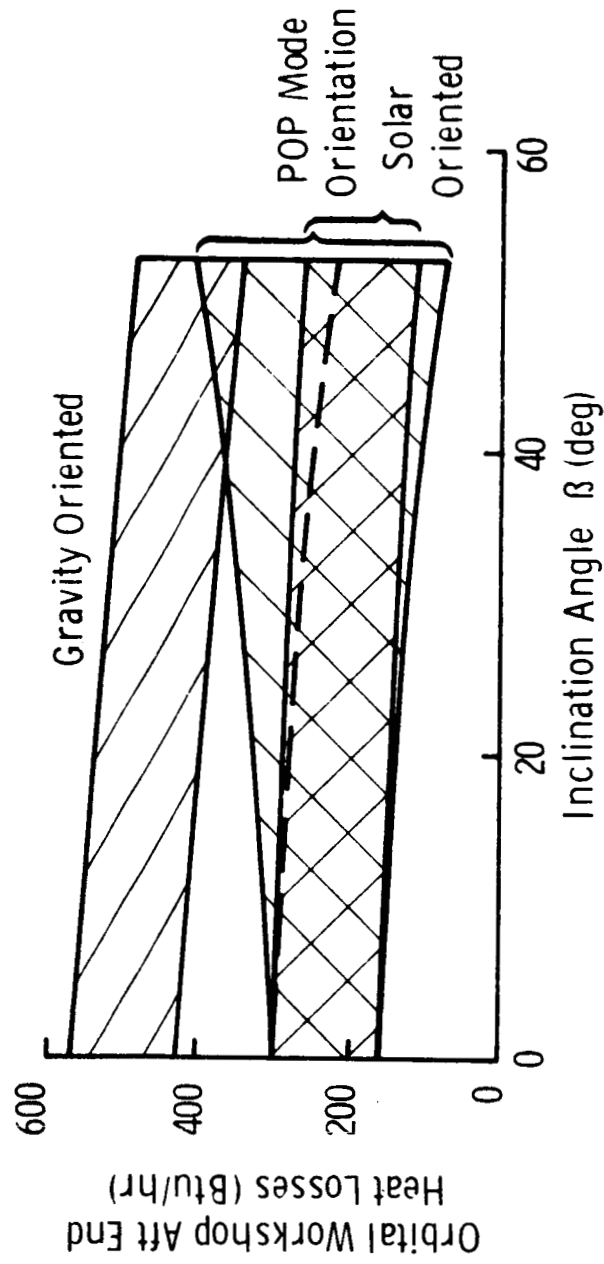


FIGURE 1 – AFT END HEAT LOSS WITH INTERNAL RADIATION HEAT SHIELD

Note: Dashed line indicates maximum POP Mode orientation
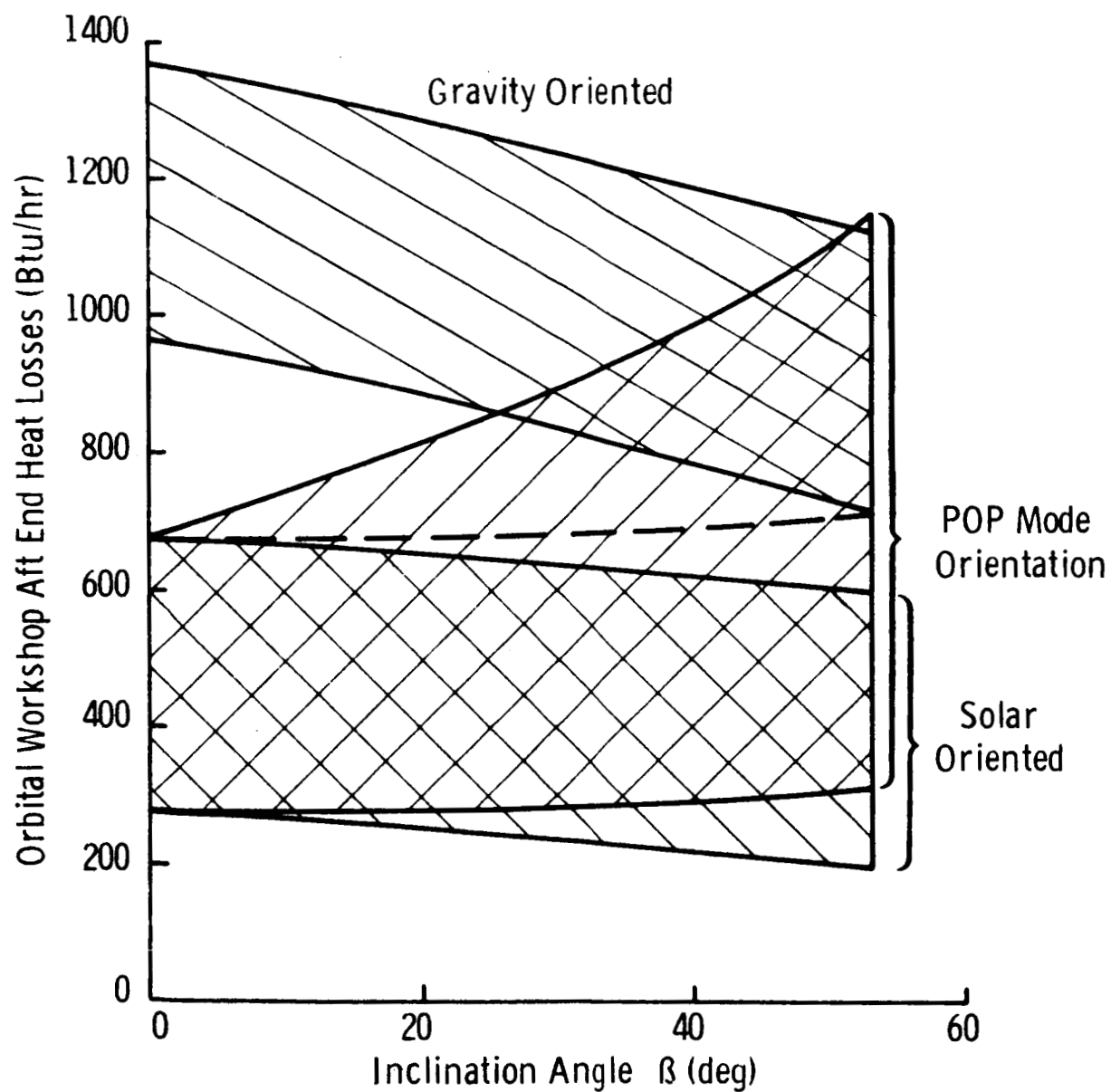heat loss for J-2 engine facing ecliptic plane

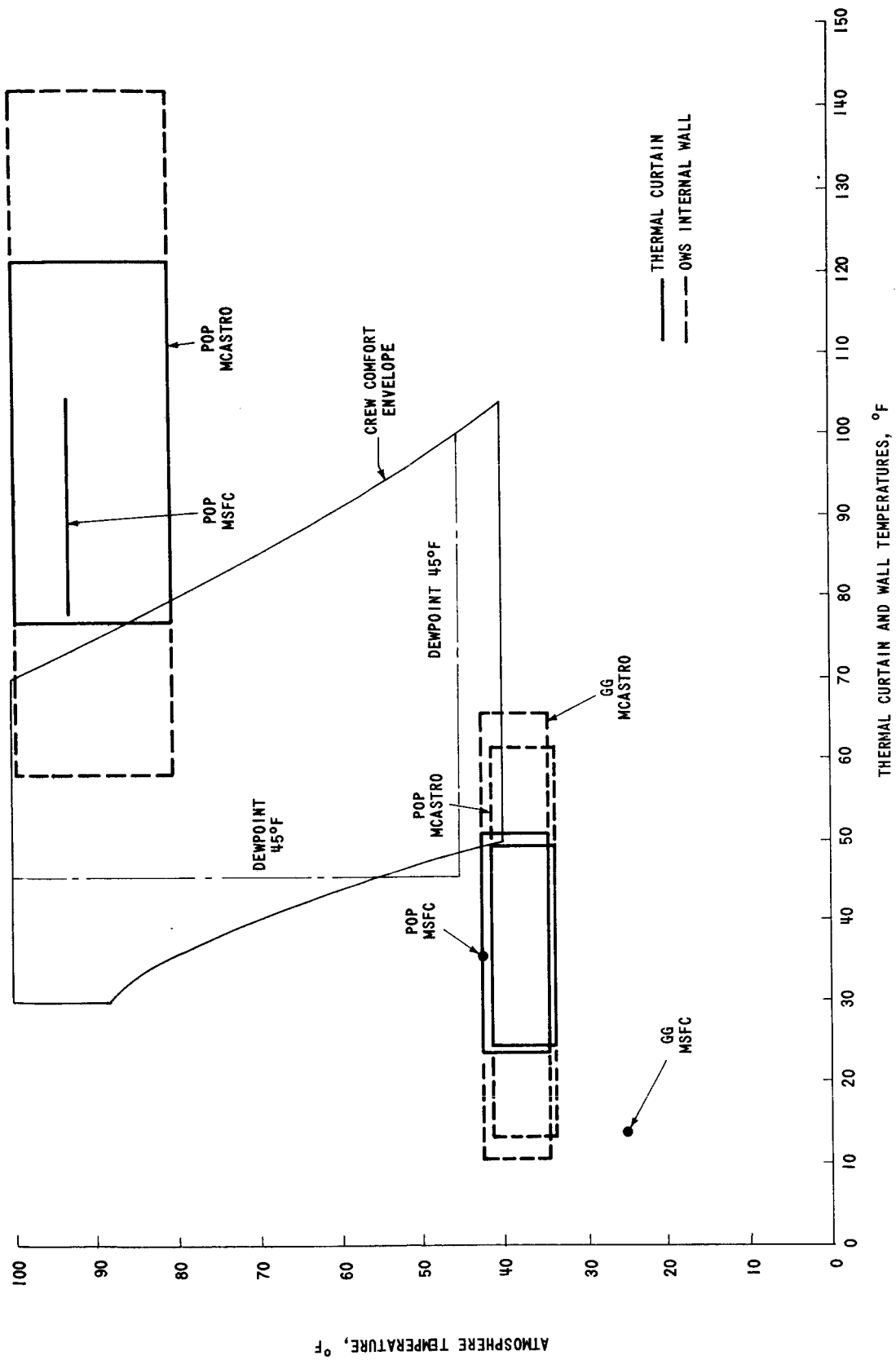FIGURE 2 – AFT END HEAT LOSS UNINSULATED PRESENT SKIRT PAINT PATTERN

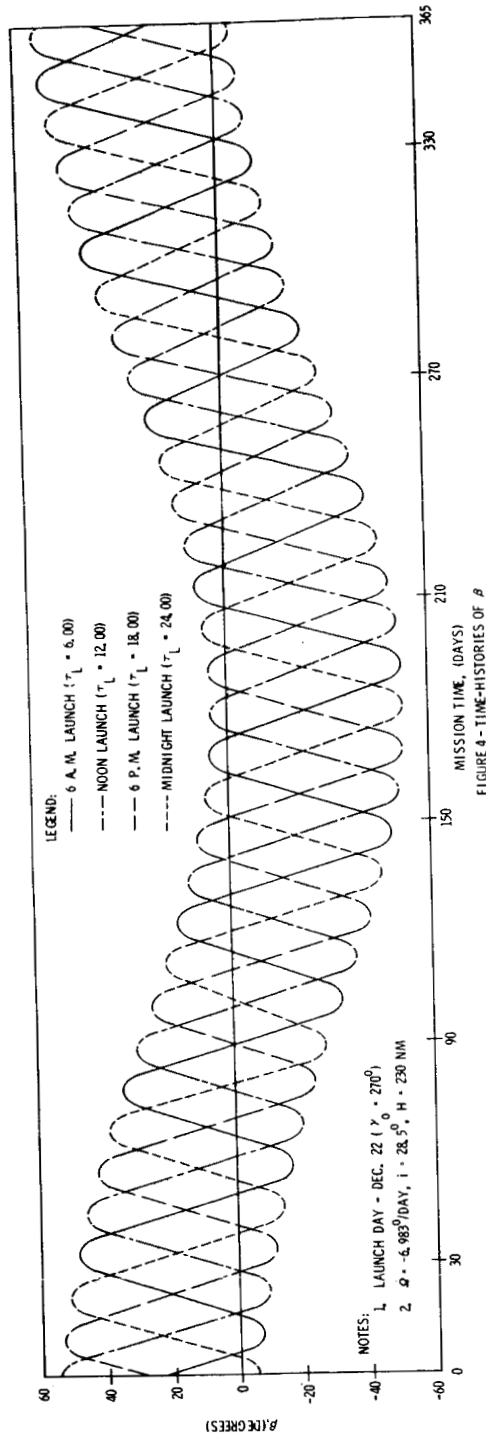FIGURE 3 - OWS TEMPERATURES FOR POP AND GG COLD AND HOT CASES

FIGURE 4 - TIME-HISTORIES OF $\beta$

MISSION TIME, (DAYS)

$\beta$, (DEGREES)

LEGEND:

——— 6 A.M. LAUNCH ($\tau_L = 6.00$)

— · · — NOON LAUNCH ($\tau_L = 12.00$)

— · — 6 P.M. LAUNCH ($\tau_L = 18.00$)

— — — MIDNIGHT LAUNCH ($\tau_L = 24.00$)

NOTES:
1. LAUNCH DAY - DEC. 22 ($\gamma_0 = 270^0$)
2. $\dot\Omega = -6.983^0/DAY$, $i = 28.5^0$, $H = 230$ NM

FIGURE 4 SHOWS $\beta$ HISTORIES FOR 230 NM
ORBITS AT A 28.5$^0$ INCLINATION. THESE ORBITS
WERE ESTABLISHED WITH A DUE-EASTERLY LAUNCH
FROM KENNEDY SPACE CENTER ON DECEMBER 22.
FOUR TIMES-OF-DAY WERE USED TO GENERATE THE
FOUR CURVES. THE ENVELOPE OF THESE CURVES
DEPENDS ONLY ON INCLINATION AND TIME OF YEAR,
AND NOT ON LAUNCH DATE AND TIME. THE UPPER
LIMITS OF THE ENVELOPE ARE (i+e) AT WINTER

SOLSTICE, (i+e) AT SUMMER SOLSTICE, AND i AT
VERNAL AND AUTUMNAL EQUINOXES. THE DIFFERENCE
BETWEEN THE UPPER AND LOWER ENVELOPE IS 2i
FOR ANY DATE. THE PERIOD OF THE ENVELOPE
VARIATION IS ONE YEAR. THE FREQUENCY OF THE
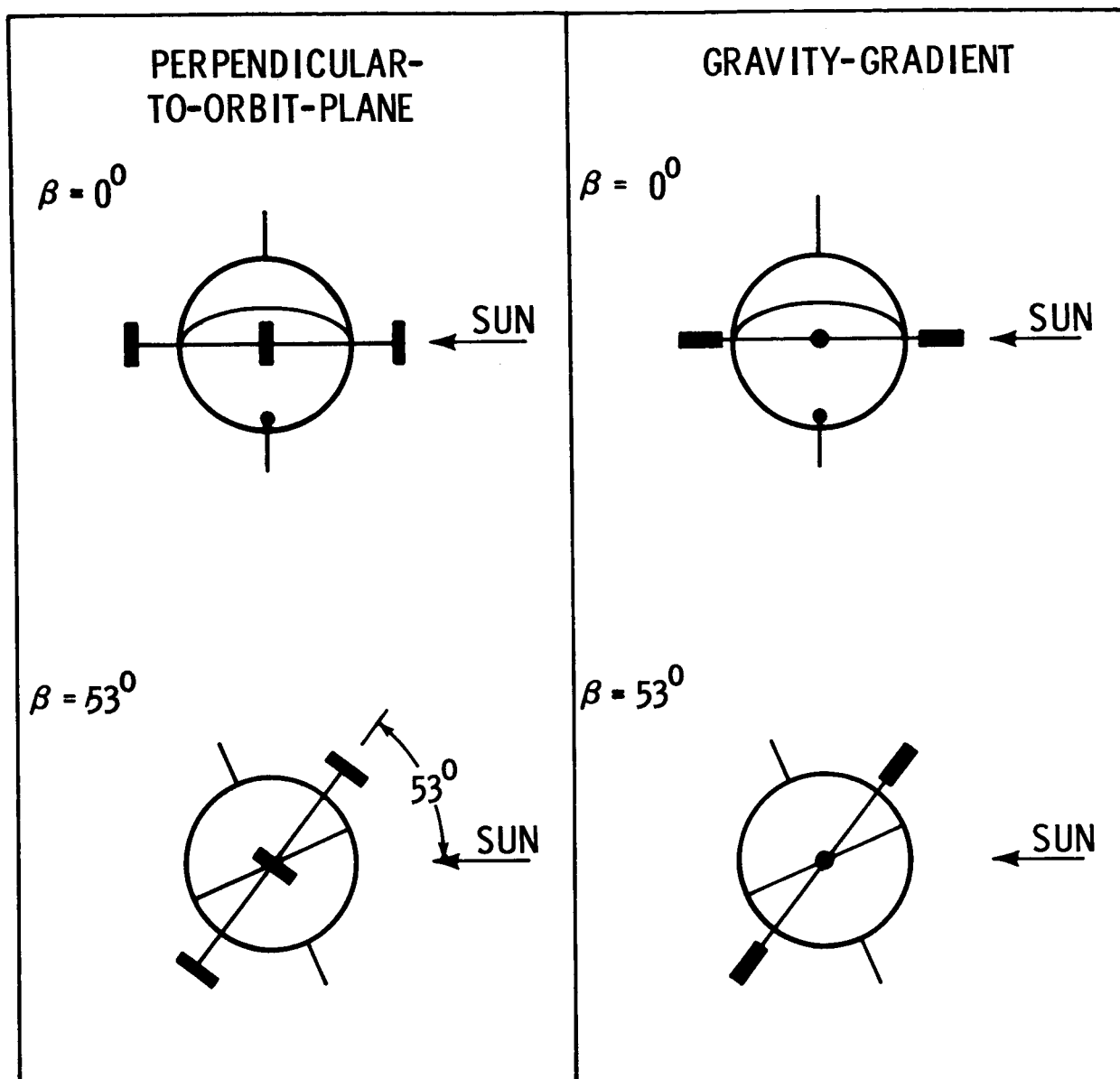VARIATION WITHIN THIS ENVELOPE IS IDENTICAL
FOR ALL CURVES.

FIGURE 5 - OWS ATTITUDES FOR POP AND GG
AT THE EXTREME $\beta$ ANGLES.
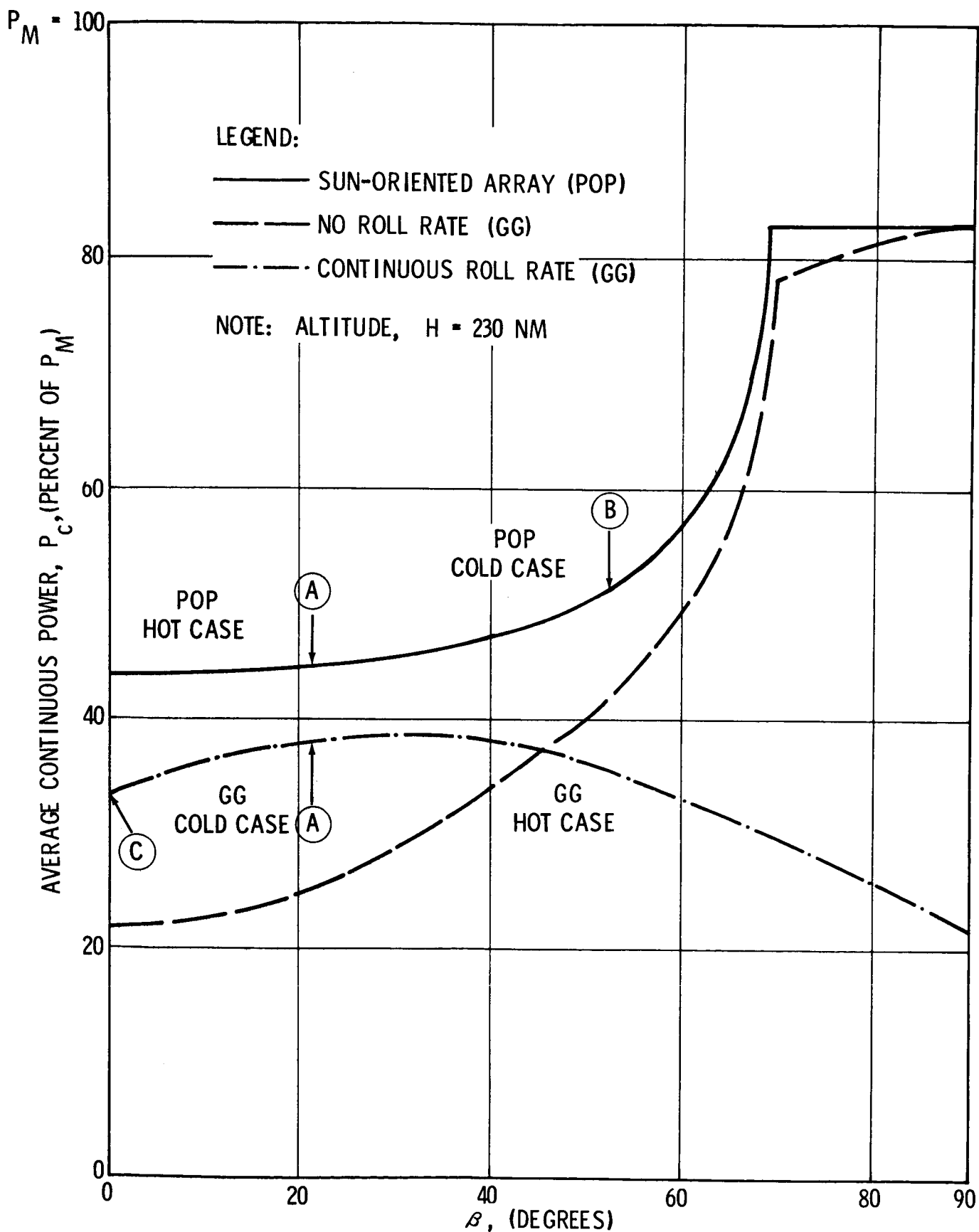
FIGURE 6 – CONTINUOUS POWER AVAILABLE AT LOAD AS A PERCENTAGE OF SUN-ORIENTED
ARRAY POWER

# APPENDIX

## INCIDENT FLUX

Approximate values of the solar $(Q_S)$, earth albedo $(Q_A)$, and earth-emitted 1R $(Q_{1R})$ thermal flux incident on the sides of an eight-sided cylinder are listed in Table A-1.[*] These values are for the different attitude orientations, $\beta$ angles, and roll profiles of interest.

The three right-hand columns are included only to show that the average incident fluxes are approximately the same, while the flux distributions over the eight sides are quite different.[**] Side 1 faces the sun and has the highest incident flux in all cases. Side 5 faces away from the sun and, together with sides 3, 4, 6, and 7, has lower colder flux values. These values show that the cold side in the GG orientation receives less incident flux than in POP and that this difference, peculiarly, is most severe in the hot cases.

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[*]Data in Table A-1 are from a memorandum in preparation by J. W. Powers, "Spacecraft Shadowing and Thermal Flux Programs."

[**]Incident load, as distinguished from incident flux, determines the net heat transferred from the environment to the interior. However, incident flux adequately makes the point that distributions are different for these cases.

TABLE A-1 - Orbital Average Incident Thermal Flux (Btu/hr ft²) for an Eight-sided Cylinder in a 230NM Earth Orbit.

$$S = 440 \text{ Btu/hr ft}^2, \text{ albedo} = 0.35, \text{ and earth temperature} = 450°R$$

| COLD CASES | | SIDE 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | AVERAGE | AVERAGE $Q_S+Q_A$ | AVERAGE $Q_S+Q_A+Q_{1R}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. GG, β=0°, continuous roll | $Q_S$ | 165.0 | 116.7 | 27.5 | 0 | 0 | 0 | 27.5 | 116.7 | 57.7 | 71.0 | 91.2 |
| | $Q_A$ | 14.4 | 14.1 | 13.3 | 12.8 | 12.6 | 12.8 | 13.3 | 14.1 | 13.3 | | |
| | $Q_{1R}$ | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | | |
| 2. GG, β=0°, no roll except 180° at subsolar | $Q_S$ | 187.5 | 132.8 | 0 | 0 | 0 | 0 | 0 | 132.8 | 59.8 | 73.6 | 93.8 |
| | $Q_A$ | 14.6 | 14.2 | 13.3 | 12.6 | 12.4 | 12.6 | 13.3 | 14.2 | 13.8 | | |
| | $Q_{1R}$ | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | | |
| 3. POP, β=53° | $Q_S$ | 184.5 | 130.4 | 0 | 0 | 0 | 0 | 0 | 130.4 | 58.7 | 68.7 | 92.9 |
| | $Q_A$ | 1.4 | 3.6 | 9.7 | 16.7 | 19.9 | 16.7 | 9.7 | 3.6 | 10.0 | | |
| | $Q_{1R}$ | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | | |

| HOT CASES | | SIDE 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | AVERAGE | AVERAGE $Q_S+Q_A$ | AVERAGE $Q_S+Q_A+Q_{1R}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. GG, β=53°, continuous roll | $Q_S$ | 203.4 | 165.4 | 76.7 | 21.6 | 0 | 21.6 | 76.7 | 165.4 | 89.9 | 98.1 | 118.3 |
| | $Q_A$ | 9.7 | 9.3 | 8.3 | 7.2 | 6.8 | 7.2 | 8.3 | 9.3 | 8.2 | | |
| | $Q_{1R}$ | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | | |
| 2. GG, β=53°, no roll except 180° at subsolar | $Q_S$ | 243.5 | 172 | 65.7 | 0 | 0 | 0 | 65.7 | 172 | 90.1 | 98.5 | 118.7 |
| | $Q_A$ | 9.7 | 9.4 | 8.4 | 7.3 | 6.9 | 7.3 | 8.4 | 9.4 | 8.4 | | |
| | $Q_{1R}$ | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | 20.2 | | |
| 3. POP, β=0° | $Q_S$ | 269.9 | 190.8 | 0 | 0 | 0 | 0 | 0 | 190.8 | 85.9 | 102.5 | 126.7 |
| | $Q_A$ | 2.2 | 5.9 | 16.0 | 27.7 | 33.0 | 27.7 | 16.0 | 5.9 | 16.6 | | |
| | $Q_{1R}$ | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | 24.2 | | |